REVIEW OF OIL SPILL REMOTE SENSORS*

M.F. Fingas and C.E. Brown
Emergencies Science and Technology Division
Environment Canada
Environmental Technology Centre
Ottawa, Ontario, Canada

ABSTRACT

Remote sensors for detecting oil spills on water are assessed in this paper. The infrared (IR) camera is a cheap and commonly available device, which can detect oil under some conditions and can discriminate oil from some backgrounds. The inherent weaknesses include the inability to discriminate oil from debris on ice and when oil is mixed with slush ice. Furthermore, water-in-oil emulsions are sometimes not detected in the infrared. The laser fluorosensor is a most useful instrument because of its unique capability to identify oil on backgrounds that include water, soil, weeds, ice, and snow. It is the only sensor that can positively discriminate oil on most backgrounds. Disadvantages include the large size, heavy weight, and high cost. Radar offers the only potential for searches over large areas, in darkness, and in foggy conditions. However, radar is costly, requires a dedicated aircraft, and is prone to many interferences. False targets can be as high as 95%. Equipment operating in the visible spectrum, such as cameras and scanners, is useful for documentation or providing a basis for the overlay of other data. It is not useful beyond this because oil shows no spectral characteristics in the visible region.

1.0 INTRODUCTION

Large spills of oil and related petroleum products in the marine environment can have serious biological and economic impacts. Public and media scrutiny is usually intense following a spill, with demands that the location and extent of the oil spill be monitored. Remote sensing is playing an increasingly important role in oil spill response efforts. Through the use of modern remote sensing instrumentation, oil can be monitored on the open ocean, around the clock. With a knowledge of slick locations and movement, response personnel can more effectively plan countermeasures in an effort to lessen the effects of the pollution.

Several general reviews of oil spill remote sensing have been prepared (Fingas and Brown, 2000a and 2000b). These reviews show that there is progress in oil spill remote sensing, but this progress is slow. Furthermore, these reviews show that specialized sensors offer advantages to oil spill remote sensing. Generic, off-the-shelf sensors have very limited application to oil spills.

2.0 OPTICAL SENSORS

2.1 Visible

While the use of human vision alone is not considered remote sensing, it is still the most

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common technique for oil spill surveillance. In the past, major campaigns using only human vision were mounted with varying degrees of success (Taft et al., 1995). Optical techniques are the most common means of remote sensing. Cameras, both still and video, are common because of their low price. Direct annotation of video images with GPS information is possible and provides useful documentation.

In the visible region of the electromagnetic spectrum (approximately 400 to 700 nm), oil has a higher surface reflectance than water, but also shows limited nonspecific absorption tendencies. The use of cameras to record slicks and subsequently to gather information about the size of the slicks is a well established technique. Video cameras are often used in conjunction with filters to improve the contrast, in a manner similar to that noted for still cameras. This technique has had limited success for oil spill remote sensing because of poor contrast and lack of positive discrimination. With new light-enhancement technology (low lux), video cameras can be operated even in darkness.

The use of visible techniques in oil spill remote sensing is largely restricted to documentation of the spill because there is no mechanism for positive oil detection. Furthermore, there are many interferences or false alarms. Sun glint and wind sheens can be mistaken for oil sheens. Biogenic material such as surface weeds or sunken kelp beds can be mistaken for oil. Oil on shorelines is difficult to identify positively because weeds look similar to oil and oil cannot be detected on darker shorelines. In summary, the usefulness of the visible spectrum for oil detection is limited. It is, however, an economical way to document spills and provide baseline data on shorelines or relative positions.

2.2 Infrared

Oil, which is optically thick, absorbs solar radiation and re-emits a portion of this radiation as thermal energy, primarily in the 8 to 14 µm region. In infrared (IR) images, thick oil appears hot, intermediate thicknesses of oil appear cool, and thin oil or sheens are not detected. The thicknesses at which these transitions occur are not known, but evidence indicates that the transition between the hot and cold layer lies between 50 and 150 µm and the minimum detectable layer is between 20 and 70 µm (Fingas et al., 1998). The reason for the appearance of the “cool” slick is not fully known. The most plausible theory is that a moderately thin layer of oil on the water surface causes destructive interference of the thermal radiation waves emitted by the water, thereby reducing the amount of thermal radiation emitted by the water.

Infrared devices cannot detect emulsions (water-in-oil emulsions) under most circumstances (Bolus, 1996). This is probably a result of the high thermal conductivity of emulsions, as they typically contain 70% water and thus do not show a difference in temperature.

Infrared cameras are now very common and commercial units are available from several manufacturers. Most infrared sensing of oil spills takes place in the thermal infrared at wavelengths of 8 to 14 µm. Tests of a mid-band IR system (3.4 to 5.4 µm) over the spills have shown variable results in detecting oil.

The relative thickness information in the thermal infrared can be used to direct skimmers and other countermeasures equipment to thicker portions of the slick. Oil detection in the infrared is not positive, however, as several false targets can interfere, including weeds, shoreline, and oceanic fronts. Infrared is reasonably inexpensive, however, and is currently the prime tool used by spill remote sensor operators.

2.3 Ultraviolet

Ultraviolet sensors can be used to map sheens of oil as oil slicks display high reflectivity of ultraviolet (UV) radiation even at thin layers (<0.01 µm). Overlaid ultraviolet and infrared images are often used to produce a relative thickness map of oil spills. Although inexpensive, ultraviolet cameras are not often used in this process, as it is difficult to overlay camera images. Data from infrared scanners and that derived from push-broom scanners can be easily superimposed to produce these IR/UV overlay maps.

Ultraviolet data are also subject to many interferences or false images such as wind slicks, sun glints, and biogenic material. Since these interferences are often different than those for infrared sensing, combining IR and UV can provide a more positive indication of oil than using either technique alone. This combination has not been used much recently due to difficulty in overlaying images from separate cameras and also because of the limited benefits

3.0 LASER FLUOROSENSORS

Laser fluorosensors are active sensors that take advantage of the fact that certain compounds in petroleum oils absorb ultraviolet light and become electronically excited. This excitation is rapidly removed through the process of fluorescence emission, primarily in the visible region of the spectrum. Since very few other compounds show this tendency, fluorescence is a strong indication of the presence of oil. Natural fluorescing substances, such as chlorophyll, fluoresce at wavelengths that are different enough than oil to avoid confusion. As different types of oil yield slightly different fluorescent intensities and spectral signatures, it is possible to differentiate between classes of oil under ideal conditions (Brown et al., 2001).

Most laser fluorosensors used for oil spill detection employ a laser operating in the ultraviolet region of 300 to 355 nm. With this wavelength of activation, there exists a broad range of fluorescent response for organic matter, centered at 420 nm. This is referred to as Gelbstoff or yellow matter, which can be easily annulled. Chlorophyll yields a sharp peak at 685 nm. The fluorescent response of crude oil ranges from 400 to 650 nm with peak centers in the 480 nm region.

Another phenomenon, known as Raman scattering, involves energy transfer between the incident light and the water molecules. The water molecules absorb some of the energy as rotational-vibrational energy and return the light as the incident energy, less this energy of rotation or vibration. The Raman signal for water occurs at 344 nm when the incident wavelength is 308 nm (XeCl laser). The water Raman signal is useful for maintaining wavelength calibration of the fluorosensor in operation, but has also been used in a limited way to estimate oil thickness, because the strong absorption by oil on the surface will suppress the water Raman signal in proportion to thickness. The point at which the Raman signal is entirely suppressed depends on the type of oil, since each oil has a different absorption strength.

Laser fluorosensors have significant potential as they may be the only means to discriminate between oiled and unoiled weeds and to detect oil on different types of beaches. The fluorosensor is also the only reliable means of detecting oil in certain ice and snow situations. A new laser fluorosensor has been built by Canadian authorities (Brown et al., 2001). This new system features a high-powered laser along with a scanning mirror.

4.0 MICROWAVE SENSORS

4.1 Radiometers

The ocean emits microwave radiation. Oil on the ocean emits stronger microwave radiation than the water and thus appears as a bright object on a darker sea. A passive device can detect this difference in emissivity and could therefore be used to detect oil. In addition, as the signal changes with thickness, in theory, the device could be used to measure thickness.

This detection method has not been very successful in the field, however, as several environmental and oil-specific parameters must be known. In addition, the signal return is dependent on oil thickness but in a cyclical fashion. A given signal strength can imply any one of two or three signal film thicknesses within a given slick. Microwave energy emission is greatest when the effective thickness of the oil equals an odd multiple of one quarter of the wavelength of the observed energy. Biogenic materials also interfere and the signal-to-noise ratio is low. In addition, it is difficult to achieve high spatial resolution.

In summary, passive microwave radiometers may have potential as all-weather oil sensors. Their potential as a reliable device for measuring slick thickness, however, is uncertain at this time.

4.2 Radar

Capillary waves on the ocean reflect radar energy, producing a “bright” image known as sea clutter. Since oil on the sea surface dampens some of these capillary waves, the presence of an oil slick can be detected as a “dark” sea or one with an absence of this sea clutter. Unfortunately, oil slicks are not the only phenomena that are detected in this way. There are many interferences or false targets, including fresh water slicks, wind slicks (calms), wave shadows behind land or structures, weed beds that calm the water just above them, glacial flour, biogenic oils, and whale and fish sperm (Fingas and Brown, 2000b). As a result, radar can be ineffective in locations such as Prince William Sound, Alaska, where dozens of islands, fresh water inflows, ice, and other features produce hundreds of such false targets. Despite these limitations, radar is an important tool for oil spill remote sensing because it is the only sensor that can be used for searches of large areas and it is one of the few sensors that can “see” at night and through clouds or fog.

The two basic types of radar that can be used to detect oil spills and for environmental remote sensing in general are Synthetic Aperture Radar (SAR) and Side-Looking Airborne Radar (SLAR). The latter is an older, but less expensive technology, which uses a long antenna to achieve spatial resolution. Synthetic aperture radar uses the forward motion of the aircraft to synthesize a very long antenna, thereby achieving very good spatial resolution, which is independent of range, at the expense of sophisticated electronic processing. While inherently more expensive, the SAR has greater range and resolution than the SLAR. In fact, comparative tests show that SAR is vastly superior. Search radar systems, such as those frequently used by the military, cannot be used for oil spills as they usually remove the clutter signal, which is the primary signal of interest. Furthermore, the signal processing of this type of radar is optimized to pinpoint small, hard objects, such as periscopes and is very detrimental to oil spill detection.

Experimental work on oil spills has shown that X-band radar yields better data than L- or C-band radar. It has also been shown that vertical antenna polarizations for both transmission and reception (V,V) yield better results than other configurations. Radar is also limited by sea state. Sea states that are too low will not produce enough sea clutter in the surrounding sea to contrast with the oil and very high seas will scatter radar sufficiently to block detection inside the troughs. Indications are that minimum wind speeds of 1.5 m/s (~3 knots) are required to allow detectability and a maximum wind speed of 6 m/s (~12 knots) will again remove the effect (Hühnerfuss et al., 1996). This limits the environmental window of application of radar to detect oil slicks.

Gade et al. (1996) studied the difference between extensive systems from a space-borne mission and a helicopter-borne system. They found that at high wind speeds, it was not possible to discriminate biogenic slicks from oil. At low wind speeds, it was found that images in the L-band showed discrimination. Under these conditions, the biogenic material showed greater damping behaviour in the L-band. Radar has also been used to measure currents and predict oil spill movements by observing frontal movements.

Shipborne radar has similar limitations and the additional handicap of low altitude, which restricts its range to between 8 to 30 km, depending on the height of the antenna. Ship radars can be adjusted to reduce the effect of sea clutter de-enhancement. The technique is very limited by sea state, however, and in all cases where it was used, the presence and location of the slick were already known.

In summary, radar optimized for oil spills is useful in oil spill remote sensing, particularly for searches of large areas and for night-time or foul weather work. The technique is highly prone to false targets, however, and is limited to a narrow range of wind speeds.

5.0 SLICK THICKNESS SENSORS

There has long been a need to measure oil slick thickness, both within the oil spill response community and among academics in the field. There are presently no reliable methods, either in the laboratory or the field, for accurately measuring the thickness of an oil slick on water. The ability to do so would significantly increase understanding of the dynamics of oil spreading and behaviour. Knowledge of slick thickness would make it possible to determine the effectiveness of certain oil spill countermeasures including dispersant application and in-situ burning. Indeed, the effectiveness of individual dispersants could be determined quantitatively if the oil remaining on the water surface following dispersant application could be accurately measured.

The suppression of the water Raman peak in laser fluorosensor data has not been fully exploited or tested. This technique may work for thin slicks, but not necessarily for thick ones, at least not with a single excitation frequency. Attempts have been made to calibrate the thickness appearance of infrared imagery, but also without success. It is suspected that the temperatures of the slick as seen in the IR are highly dependent on oil type, sun angle, and weather conditions. It is not possible to use IR as a calibrated tool for measuring thickness.

A variety of electrical, optical, and acoustic techniques for measuring oil thickness has been investigated (Goodman et al., 1997). Promising techniques were pursued in a series of laboratory measurements. The most promising technique involves laser acoustics (Brown et al., 2000). The Laser Ultrasonic Remote Sensing of Oil Thickness (LURSOT) sensor consists of three lasers, one of which is coupled to an interferometer to accurately measure oil thickness (Brown et al., 2000). The sensing process is initiated with a thermal pulse created in the oil layer by the absorption of a powerful CO_2 laser pulse. Rapid thermal expansion of the oil occurs near the surface where the laser beam was absorbed, which causes a step-like rise of the sample surface as well as an acoustic pulse of high frequency and large bandwidth (~ 15 MHz for oil). The acoustic pulse travels down through the oil until it reaches the oil-water interface where it is partially transmitted and partially reflected back towards the oil-air interface, where it slightly displaces the oil's surface. The time required for the acoustic pulse to travel through the oil and back to the surface again is a function of the thickness and the acoustic velocity of the oil. The displacement of the surface is measured by a second laser probe beam aimed at the surface. Motion of the surface induces a phase or frequency shift (Doppler shift) in the reflected probe beam. This phase or frequency modulation of the probe beam can then be demodulated with an interferometer. The thickness can be determined from the time of propagation of the acoustic wave between the upper and lower surfaces of the oil slick. This is a very reliable means of studying oil thickness and has great potential.

6.0 SATELLITE REMOTE SENSING

Recently, it has been strongly suggested that satellite remote sensing could replace airborne remote sensing for detecting oil spills. However, current technologies do not support this claim. Satellite remote sensing has been used for detecting oil spills, especially in earlier years, when satellites provided imagery in the visible region of the spectrum. The slick from the IXTOC I well blowout in Mexico was detected using GOES (Geostationary Operational Environmental Satellite) and also by the AVHRR (Advanced Very High Resolution Radiometer) on the LANDSAT satellite (Fingas and Brown, 2000b). A blowout in the Persian Gulf was subsequently detected. The massive EXXON VALDEZ slick was detected on SPOT (Satellite Pour l'Observation de la Terre) satellite data. Oiled ice in Gabarus Bay resulting from the KURDISTAN spill was detected using LANDSAT. Several workers were able to detect the Arabian Gulf War Spill by satellite in 1991. It is significant to note that, in all these cases, the position of the oil spill was known and data had to be processed to actually see the oil, which usually took several weeks.

There are several problems associated with relying on satellite imagery, especially in the visible spectrum, for oil spill remote sensing. The first is the timing and frequency of overpasses and the absolute need for clear skies to perform optical work. The chances of the overpass and the clear skies occurring at the same time give a very low probability of seeing a spill on a satellite image. This point is well illustrated in the case of the EXXON VALDEZ spill. Although the spill covered vast amounts of ocean for over a month, there was only one clear day (April 7, 1989) that coincided with a satellite overpass. Another disadvantage of satellite remote sensing is the difficulty in developing algorithms to highlight the oil slicks and the long time required to do so. For the EXXON VALDEZ spill, it took over two months before the first group managed to "see" the oil slick in the satellite imagery, although its location was precisely known.

In its present state, optical satellite imagery does not offer much potential for oil spill remote sensing. Radar satellites, however, offer much greater potential. Oil on a sea surface dampens the small capillary waves that are normally present on clean seas. These capillary waves reflect radar energy, producing a "bright" area in radar imagery known as sea clutter. The presence of an oil slick can be detected as a "dark" area or one with an absence of sea clutter. Unfortunately, oil slicks are not the only phenomenon that can be detected in a similar manner. There are many potential interferences, including fresh water slicks, calm areas (wind slicks), wave shadows behind land or structures, vegetation or weed beds that calm the water just above them, glacial flour, biogenic oils, and whale and fish sperm. Automated systems of oil detection have not had great success because of these many false images.

Despite these limitations, radar is an important tool for oil spill remote sensing since it is the only sensor capable of searching large areas. Radars, being active sensors operating in the microwave region of the electromagnetic spectrum, are one of the few sensors that can "see" at night and through clouds or fog. Radar satellites, including ERS-1 and -2, Radarsat-1, and JERS-1, have been useful for mapping known large offshore spills. Radarsat has been used for detecting oil seeps.

All satellite data suffer from problems of resolution and timeliness. A comparison of the use of satellite- versus airborne-derived data showed that satellite data lacks resolution and timeliness for many oil spill applications (Fingas and Brown, 1997).

Several new satellites will be launched in the future, enhancing current capability. Of particular note are the new radar satellites that will offer increased resolution and polarimetric capability. It should be noted that existing and future satellites have little potential for the detection of oil with or on ice. There is no detection mechanism for oil in this situation and the fact that ice calms the water means that oil detection near ice using radar is severely handicapped.

Jones (2001) compared the oil distribution from airborne visual observation with that from radar satellites. There was good correspondence between the visual observations and that from satellites. It was noted that slick detection was only observed between the wind speed of 2 to 12 m/s as noted above, but thinner sheens appeared more at the lower winds speeds and vice versa. The optimal wind speed for identifying thick oil in SAR imagery was about 5 to 6 m/s. Because of the influence of shore and headlands, nearshore oil distribution was unreliable. Jones concludes that because of the poor time coverage of radar satellites, they are not suited for operational use.

7.0 REAL-TIME DISPLAYS AND PRINTERS

A very important aspect of remote sensing is the production of data that operations people can use quickly and directly. Real-time displays are important so that remote sensor operators can adjust instruments directly in flight and provide information quickly on the location or state of a spill. A major concern of the client is that data be rapidly available. At this time, existing hardware and software must be adapted, as commercial off-the-shelf equipment for directly outputting and printing specific sensor data is not yet available, although some sensors are now provided with this capability.

8.0 FUTURE TRENDS

Advances in sensor technology will continue to drive the use of remote sensors as operational oil spill response tools in the future. Thermal infrared detectors that offer high sensitivity without the need for cooling are readily available in the marketplace. This improvement not only reduces the size and complexity of the sensor, but also the cost. In the next decade, advances in solid-state laser technology, in particular diode-pumped, solid-state lasers, will greatly reduce the size and energy consumption of laser-based remote sensors. This will promote the use of these sensors in smaller aircraft within the budget of many more regulatory agencies and maritime countries. At the present time, there is no single "Magic Bullet" sensor that will provide all the information required to detect, classify, and quantify oil in the marine and coastal environment.

9.0 REFERENCES

R.L. Bolus, “Airborne Testing of a Suite of Remote Sensors for Oil Spill Detecting on Water”, in *Proceedings of the Second Thematic International Airborne Remote Sensing Conference and Exhibition*, Environmental Research Institute of Michigan (ERIM), Ann Arbor, MI, pp. III743-752, 1996.

C.E Brown, M.F. Fingas, R.H. Goodman, J.V. Mullin, M. Choquet, and J-P. Monchalin, “Airborne Oil Slick Thickness Measurement”, in *Proceedings of the Sixth International Conference on Remote Sensing for Marine and Coastal Environments*, Veridian ERIM International, Ann Arbor, MI, pp. I219-224, 2000.

C.E Brown, M.F. Fingas, and J. An, “Laser Fluorosensors: A Survey of Applications and Developments of a Versatile Sensor”, in *Proceedings of the Twenty-Fourth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, ON, pp. 485-493, 2001.

M.F. Fingas, and C.E. Brown, “Airborne Oil Spill Remote Sensors - Do They Have a Future?”, in *Proceedings of the Third International Airborne Remote Sensing Conference and Exhibition*, Environmental Research Institute of Michigan (ERIM), Ann Arbor, MI, pp. I 715-722, 1997.

M.F. Fingas, C.E. Brown, and J.V. Mullin, “The Visibility Limits of Oil on Water and Remote Sensing Thickness Detection Limits”, in *Proceedings of the Fifth Thematic Conference on Remote Sensing for Marine and Coastal Environments*, Environmental Research Institute of Michigan (ERIM), Ann Arbor, MI, pp. II 411-418, 1998.

M.F. Fingas, and C.E. Brown, “Review of Oil Spill Remote Sensing”, in *Proceedings of the Sixth International Conference on Remote Sensing for Marine and Coastal Environments*, Veridian ERIM International, Ann Arbor, MI, pp. I211-218, 2000a.

M.F. Fingas, and C.E. Brown, “Review of Oil Spill Remote Sensing”, in *Proceedings of SPILLCON 2000*, Australian Marine Safety Authority, Sydney, Australia, www.meetingplanners.com.au/spillcon/, 2000b.

M. Gade, W. Alpers, H. Hühnerfuss, and V. Wismann, “Radar Signatures of Different Oceanic Surface Films Measured during the SIR-C-X-SAR Missions”, in *Remote Sensing (96), 16th Symposium of the European Association of Remote Sensing Laboratories (EARsel)*, Rotterdam, Holland, pp. 233–240, 1996.

R. Goodman, H. Brown, and J. Bittner, “The Measurement of Thickness of Oil on Water”, in *Proceedings of the Fourth Thematic Conference on Remote Sensing for Marine and Coastal Environments*, Environmental Research Institute of Michigan (ERIM), Ann Arbor, MI, Vol. I, pp. 31-41, 1997.

H. Hühnerfuss, W. Alpers, H. Dannhauer, M. Gade, P.A. Lange, V. Neumann, and V. Wismann, “Natural and Man-made Sea Slicks in the North Sea Investigated by a Helicopter-borne 5-frequency Radar Scatterometer”, *Int. J. Remote Sensing*, Vol. 17, No. 8, pp. 1567-1582, 1996.

B. Jones, “A Comparison of Visual Observations of Surface Oil with Synthetic Aperture Radar Imagery of the *Sea Empress* Oil Spill”, *International Journal of Remote Sensing*, Vol. 22, No. 9, pp. 1619-1638, 2001.

D.G. Taft, D.E. Egging, and H.A. Kuhn, “Sheen Surveillance: An Environmental Monitoring Program Subsequent to the 1989 Exxon Valdez Shoreline Cleanup”, in *Exxon Valdez Oil Spill: Fate and Effects in Alaskan Waters*, ASTM STP 1219, American Society for Testing and Materials, PA, pp. 215-238, 1995.